Development of a Turn Key Cryogenic Cooling Module for Space Flight Based on a Commercial Cryocooler

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Commercial cryocoolers have significant price and lead time advantages over coolers built exclusively for the space market, but there are many challenges that must be overcome before using a COTS cooler for flight. The initial cost advantage is significantly narrowed by the cost of adapting the COTS cooler for flight. JPL is developing a "turn key" cryogenic cooling solution based on a commercial cryocooler with the intention that it can become a standard product. The goal is to develop a complete, fully redundant cryogenic cooling solution based on the Thales 9310. The system includes the cooler, brackets to provide mounting and cooling, supporting structures, vibration isolation, thermal straps, thermal switches, and drive electronics. This paper discusses qualification of the various components for flight, including launch vibration and thermal performance testing, as well as a full up testing of the completed assembly.

I. Introduction

There is considerable interest in using commercial coolers for space flight programs. The cost and schedule advantages of commercial coolers are substantial. There are several difficulties that must be dealt with when attempting to use one for space flight. The primary problem is that commercial coolers typically do not include mechanical and thermal interfaces required for flight. The typical ground based system bolts the cold head to a vacuum dewar, while clamping the compressor in place with a band clamp. The entire assembly is air cooled. This is unacceptable for space flight because of the acceleration loads imposed by launch (random vibration and directed acceleration) and because of the need to conductively couple the heat producing elements to a cold sink. Another problem with commercial coolers in flight is vibration. Even opposed-piston compressors generate considerably more vibration than comparable flight-like coolers due to their larger detailed component tolerances that are due to their lower cost.

A second issue is electronics. While the commercial suppliers produce drive electronics suitable for ground operation, these devices have several shortcomings for use in flight. The primary issue is radiation. The susceptibility of commercial devices to radiation upsets is generally unknown. Some amount of vibration control is desired. Health and status telemetry. Use of diodes for sensing temperature is good for ground operation, but they may not be suitable due to parameter shifts due to in flight radiation. A robust set of electronics is required for space flight operation.

While there are a number of commercial cryocoolers that have been or could be flown, JPL has found the Thales series of pulse tube coolers to be useful starting point for a flyable system. The Thales 9310 is representative of this class of coolers, consisting of a dual opposed piston compressor and a remote coldhead/expander unit, connected by a short transfer tube. Figure 1 shows a standard configuration of the 9310. The cooler has a cooling capacity of about 5 W at 77 K.

This paper describes a turnkey cryocooler system, suitable for incorporation into a flight system. This is being designed and built without a specific program in mind; rather, it is intended to be a drop-in cooling system that could be used as-is or tailored for a specific set of flight requirements. The conceptual program requires full redundancy and vibration isolation. Vibration isolation takes two forms, isolation of the Thermo-Mechanical Unit (TMU) from launch random vibration loads and isolation of the platform from vibration generated by the TMU during operation. The TMU will be cooled through constant conductance heat pipes; the other end of the heat pipe is assumed to be coupled to a cold sink, without attempting to specify the exact conditions

II. Mechanical Configuration

Figure 1 depicts the cooler assembly: a platform that supports the redundant TMUs, a structure that supports the entire assembly, vibration isolators that go between the platform and structure, and heat pipes to remove the waste

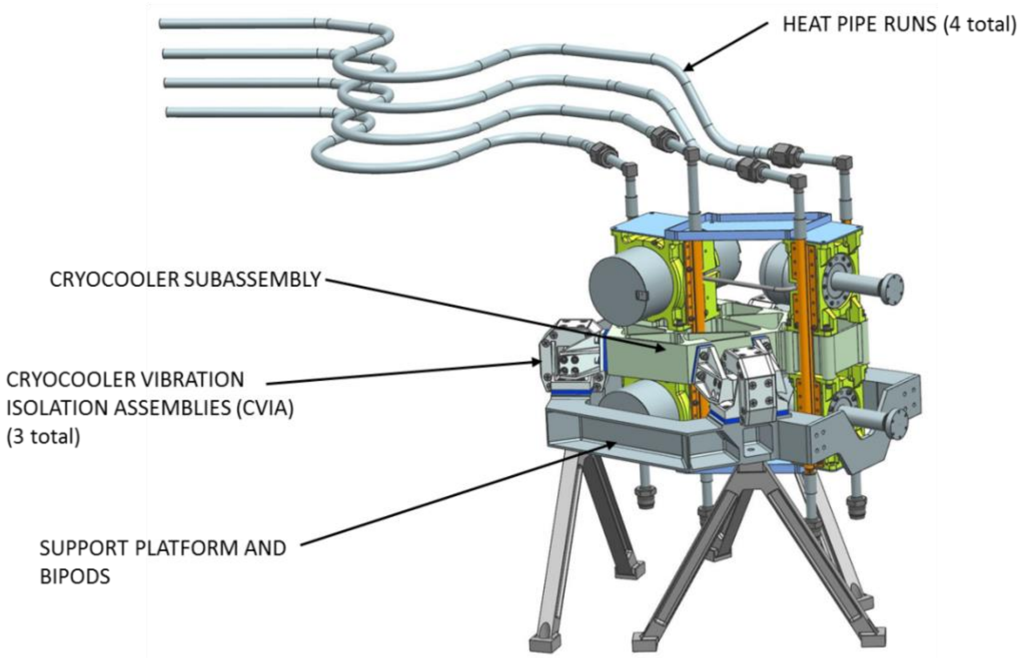

Figure 1 Overall configuration of dual cryocooler assembly

heat from the TMUs. Not shown are the flexible thermal straps that conductively connect the cold head to the payload, thermal switches that isolate a non-operating cooler from the payload, and redundant drive electronics to power and control the TMUs.

The first issue is the mechanical clamp that hold the cryocooler. These serve double duty: securely holding the TMU components in place and providing a conductive path for heat removal. The Thales 9310 is a split cooler. Testing at JPL has shown that roughly 55% of the waste heat rejection is at the compressor and 45% at the expander. The compressor heat rejection is concentrated within about 25 mm of the center. The expander heating is concentrated at the neck of the expander, between the mounting flange and expansion volume. Clamps that fit over the required area and provide mounting location for heat pipes. Since heat pipe evaporator length is a driving performance parameter, the surface was made as long as practical. The clamps are 6061 aluminum. While other alloys can provide better thermal performance, consideration of strength in a large block drove the design to 6061-T6. The installed clamps are shown in Figure 2.

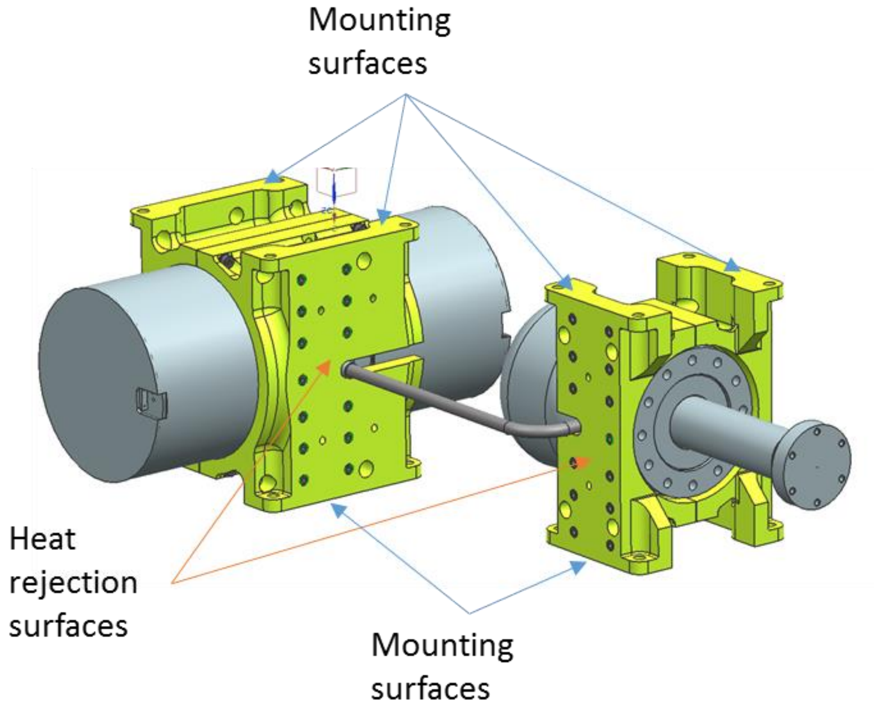

Figure 2. Cooling and structural support blocks

The interface between the clamp and body is made with low volatility, high thermal conductivity RTV. To maximize the thermal performance the bondline should be as thin as possible, but the bond thickness must be enough to tolerate the differential expansion and contraction between the aluminum clamp, stainless steel TMU, and RTV. Clamps are bolted together; centering of the TMU in the clamp is controlled with wire.

At maximum operating power the expander skin is expected to be 13°C warmer than the vapor nodes of the attached heat pipes. This analysis includes the temperature drop through the adhesive, conduction in the clamp, conduction through the interface material to the heat pipe flange, and evaporation of the heat pipe working fluid. The compressor, though dissipating 100 W, is expected to run about 10°C above vapor node. The clamps are designed to accommodate a single heat pipe failure, forcing all the heat to one side. In this case the components will run about 12°C warmer still. This will result in a reduction in cooling of about 12%. While this is a performance reduction, it is within the normal margins that are carried in actively cooled systems.

The clamps are to be bolted to a tray that supports the two TMUs. The tray is designed to prevent relative motion between the compressor and expander. This is necessary to keep from imposing structural loads on the transfer tube, and to prevent amplification of harmonics generated by cooler operation. Practically, this means that the lowest mode allowing relative motion is above the third harmonic of the operating frequency of the cooler. The tray is also 6061-T6 aluminum. Installation of the cryocoolers on the tray is depicted in Figure 3.

The support platform consists of a horseshoe shaped ring, which the vibration isolators are mounted to. The ring is split to allow the lower TMU to pass through. A closeout plate completes the ring. As shown, rigid bipods are used to hold the support ring off a conceptual spacecraft deck. Since there is not a specific program to design to, this notional support structure was made to be able to conveniently support the system off of a dynamometer or vibration test shaker.

Vibration isolators connect the platform to the tray. The isolators were designed by MOOG CSA Engineering. The isolators serve two purposes, isolation of launch vibration and isolation of exported vibration of operation. The isolators consist of four visco-elastic cylinders in a “+” pattern, with the tips of the cross rigidly attached to the support pedestal and the center connected to the Cryocooler Assembly Tray. The first six modes of the completed assembly are in a band from approximately 20-30 Hz.

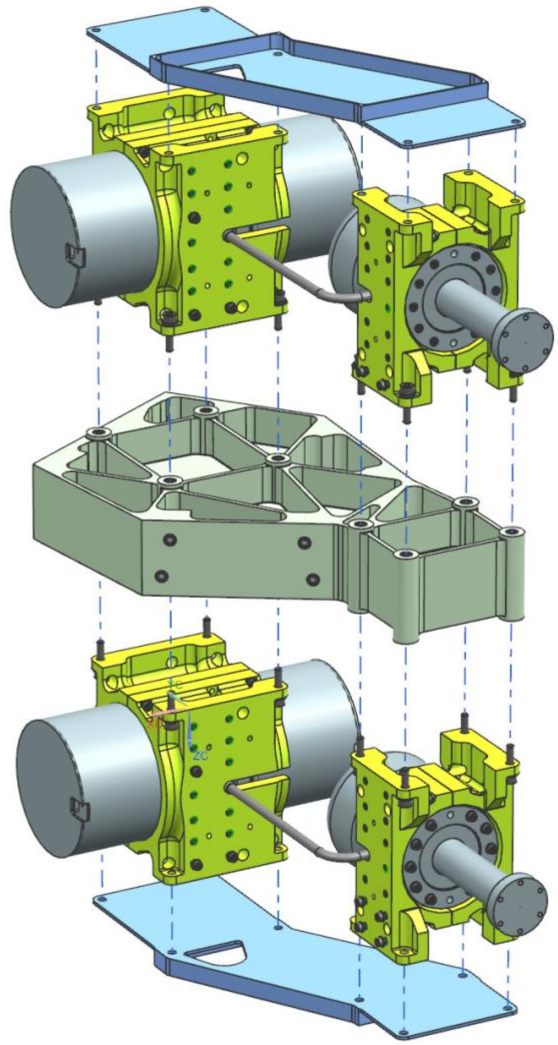

Figure 3. Support Tray and Shear Plates Produce Isolated Structure

Useful cooling of the payload is provided through flexible straps provided by Thermotive. The conductive material is a graphite foil, permanently attached to aluminum end blocks. The end blocks are designed to interface with the 9310 coldhead bolt pattern.

The conductive performance of the composite straps has been tested from 60 K to 300 K. Figure 4 shows a summary of strap test results, previously published in Reference 1. Three groups of data are shown in the figure: an aluminum strap with a 75 mm long flex section, a composite strap with a 75 mm long flex section, and a composite strap with a 150 mm long flex section. Composite strap thermal performance significantly exceeds aluminum over most temperatures, but at 60 K the performance of the two become equal. The strap has also been tested for particle generation during large deflection cycles and shown to produce no measurable contaminant.

Switches were designed to match the straps, i.e. to have the same bolt pattern as the 9310. The switches were provided by ATK, Beltsville, MD, based on the design of Reference 2. Two switches were built. On conductance was measured at ATK using a heater on the body of the switch with the cap connected to a cryocooler. The lowest "on" conductance measured was 2.5 W/K, with some results as high as 5 W/K. The "off" conductance has been measure at

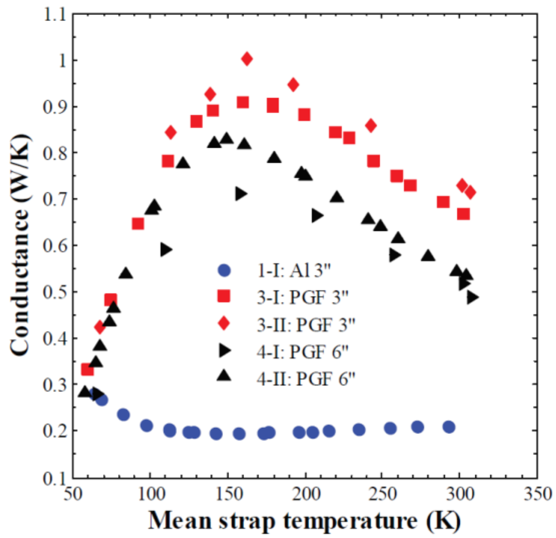

Figure 4. Thermal strap performance test shows performance of composite thermal straps down to 60 K.

JPL, with results in Figure 5. In a full two-cooler configuration with one cooler running and driving the payload to 100 K, the top of the switch connected to the non-operating cooler is expected to be about 260 K. Resistance in this condition is about 2.5 mW/K, resulting in a heat load of about 400 mW from the non-operating cooler.

Electronics are provided by Iris. The Iris electronics are based on previous designs (Reference 3) with two modifications for this project. The first is the maximum power of 200 W, in order to drive the 9310 at its maximum power of about 175 W. Vibration control has been extended to the first five harmonics.

III. Qualification Test Program

The testing program that will lead to flight qualification of the turnkey assembly includes launch vibe, exported vibration, EMI, thermal cycling, and operating thermal performance. Previous testing on the Thales 9310 in a rigid

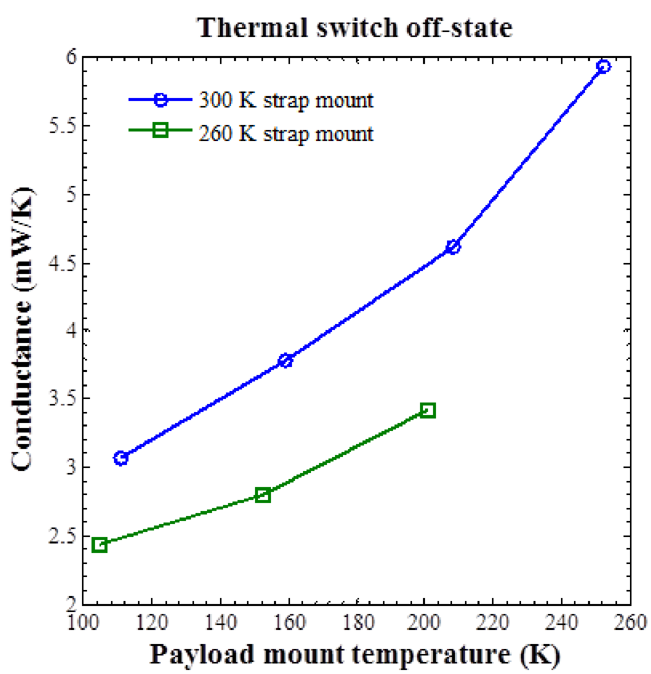

Figure 5. Thermal Switch Off Conductance

fixture was performed to determine coldhead and compressor response to random vibe. Launch vibration testing on the assembly was completed in November 2015.

The random vibration testing was performed in three orthogonal directions with inputs at the feet as shown in Table 1. This was selected to represent a typical proto-qualification launch profile. “S” shaped pipes were attached to represent a bank of constant conductance heat pipes connected to a fixed radiator. The assembly was instrumented with 10 tri-axial accelerometers (30 channels total) as shown in Figure 6..

Electrical aliveness checks on both coolers were performed between each test, consisting of operating each cooler at a fixed power level and measuring the time required to cool down the cold tip by 5 deg C.

The first series of tests was parallel to the cold head centerline, designated the X axis. Profiles were stepped up from -18 dB to full level. Because of concern about heating of the viscoelastic isolators, the full level test was run in two 30 second segments. The low level sweep was repeated after full level, and repeated again after a 15 minutes cool down. No change in response of the accelerometers was seen, which indicates that the isolator performance does not change significantly due to heating. The test was repeated in the compressor axis and vertical. No shifts were observed between pre- and post-test results.

A typical result is shown in Figure 7. This shows the response in the X-axis of an accelerometer mounted to the side of the Cryocooler Subassembly Tray. The expected resonance at about 25 Hz with a strong roll off to 200 Hz is shown. This response matches the prediction very closely and demonstrated that the isolation system provided the requisite damping to effectively reduce the vibration input seen by the cryocoolers to an acceptably low level

Tests were repeated in Y and Z, again closely matching predictions. Aliveness tests showed no change in performance, demonstrating that the system can survive a very strong launch random environment.

Demonstration of the isolation system’s ability to damp exported vibration and torque remains to be completed.

Thermal performance of the Thales 9310 has been tested at JPL, with results reported in Reference 4. Initial tests used a very heavy mounting structure cooled at the baseplate. Re-test using a previous version of the flight clamp has shown no degradation in performance, which indicates that the cooling performance of the assembly will be similar to the previous test results.

The assembled unit is depicted in Figure 8, being prepared for thermal testing..

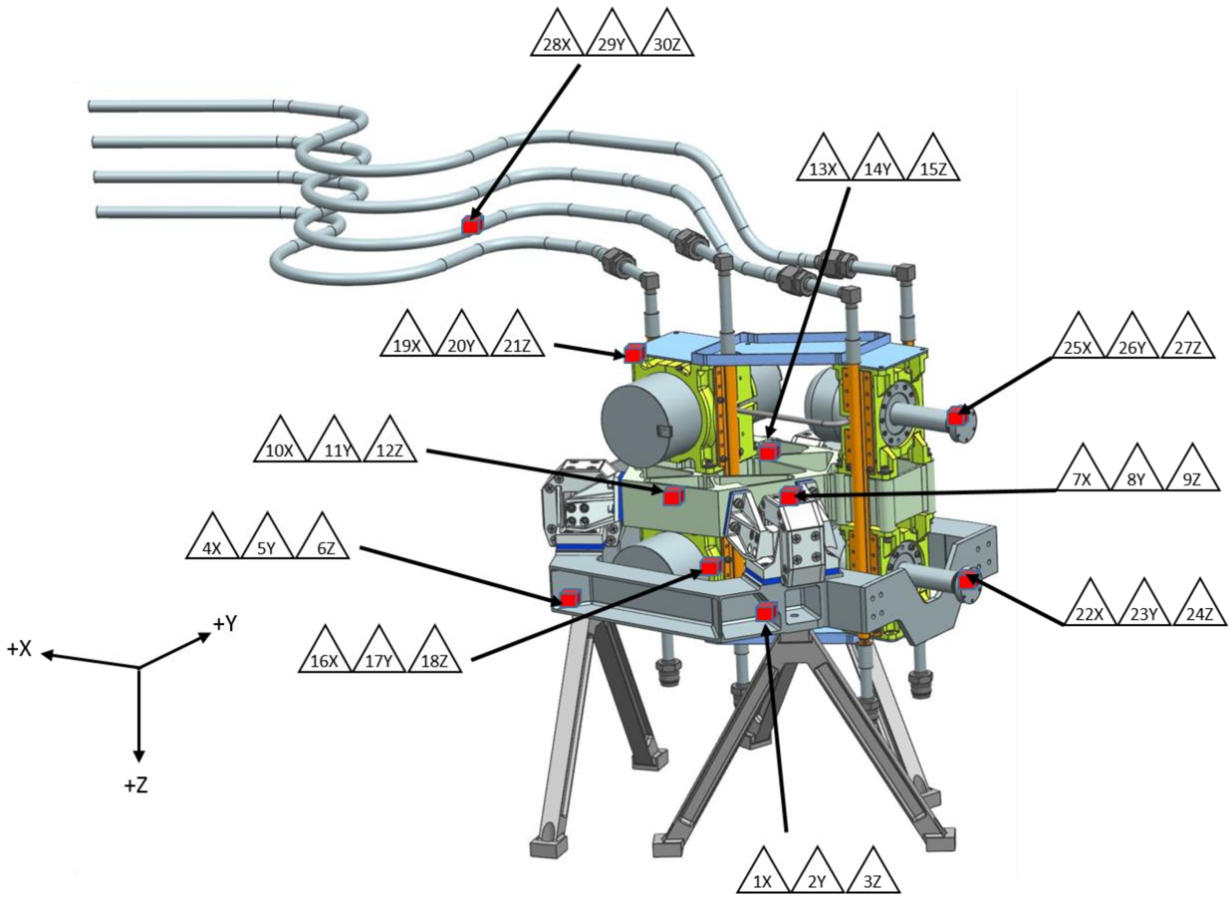

Figure 6. Placement of Accelerometers for Random Vibe Test

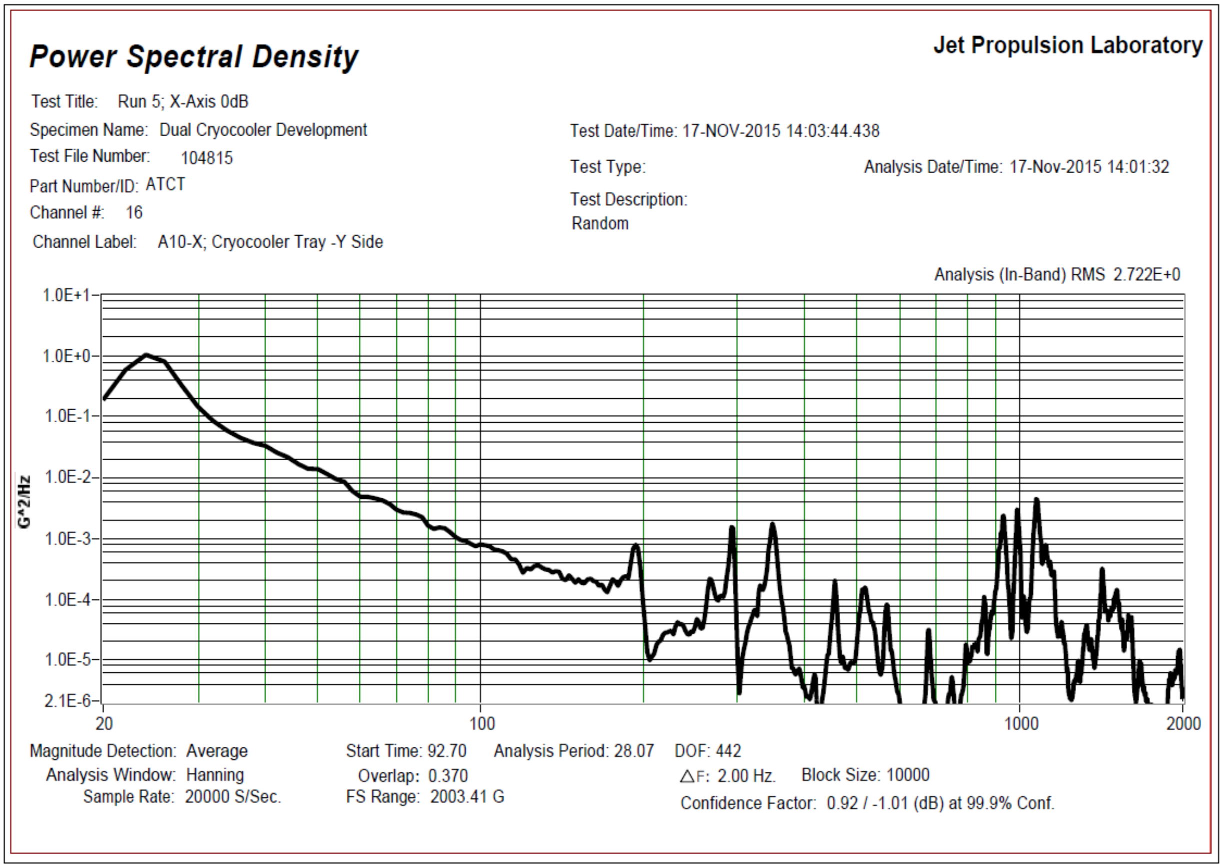

Figure 7. Response of accelerometer on the tray, X-axis test at full level. Response shows the expected peak at 25 Hz and rolls off almost 4 decades to 200 Hz.

IV. Conclusion

Significant progress has been made toward creating a flyable, fully redundant cryocooling system based on the Tlales 9310 cryocooler. Components required to support operation have been built and tested. The TMU assembly has been random vibration tested to a typical launch input profile.

Acknowledgments

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Table 1. Vibration Test Environment

Frequency (Hz)	Protoflight Test Level
20	0.026 g^2/Hz
20-50	+6 dB/octave
50-500	0.16 g^2/Hz
500-2000	-4.5 dB/octave
2000	0.02 g^2/Hz
G_{rms} overall	12.4 grms
Test Duration is 60 seconds per axis	

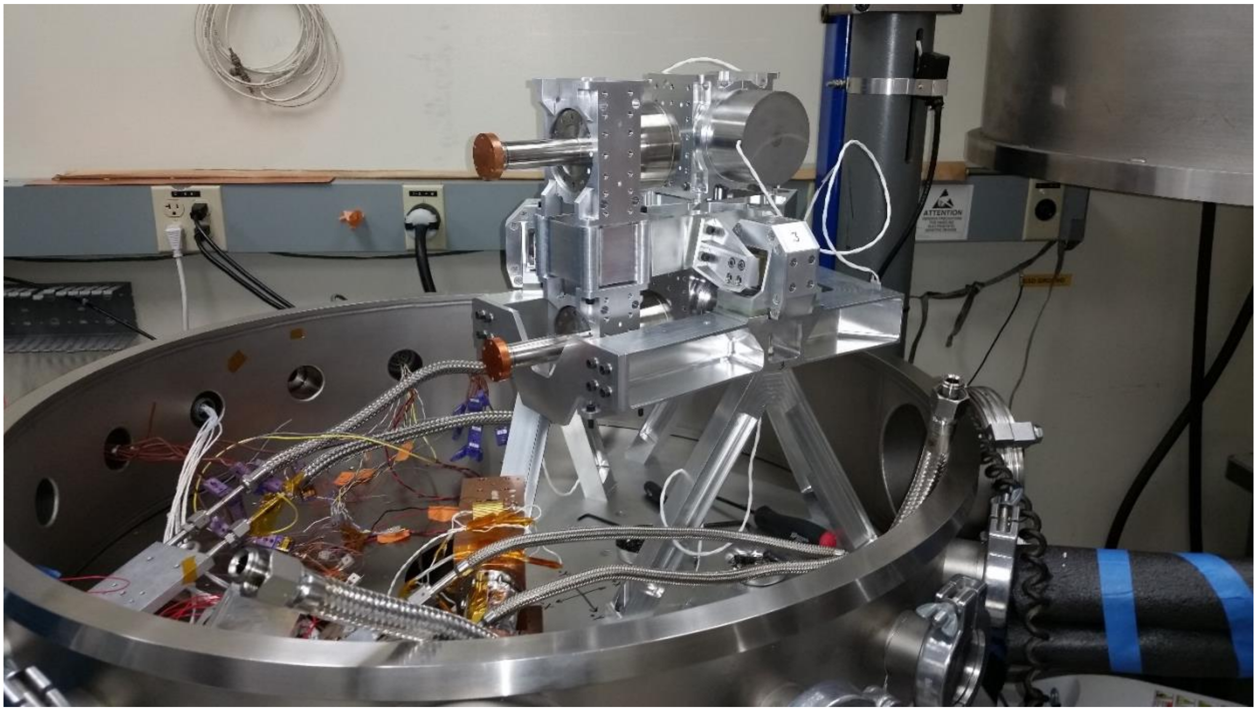

Figure 8. Assembled unit being prepared for thermal vacuum test